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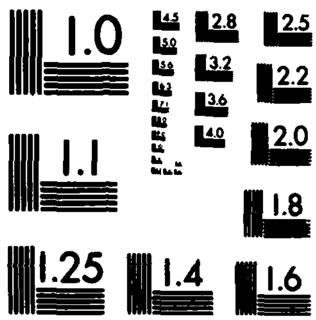

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FINAL SCIENTIFIC REPORT

THE EFFECT OF BODY FORCES ON THE MOTION AND HEAT TRANSFER OF CONFINED FLUIDS

Grant AFOSR-81-0045
January 31, 1983

The research performed under the subject grant dealt with two problems in which body forces lead to complex flows which are of scientific and technological importance. The first of these is concerned with the central unresolved problem of flows in completely confined enclosures, viz., that it is not possible to predict the flow pattern a priori for a specified geometric configuration and imposed boundary conditions. The second problem is an external one in which there is an interaction of hydrodynamic (Taylor-Görtler) and thermal (Rayleigh-Bénard) instabilities. The details of the work done are presented below.

Natural Convection in Shallow Enclosures

Natural convection in enclosures is encountered in many technologies such as materials processing, crystal growth, solar energy receivers, and fluids storage and management. The associated transport phenomena are complex and have been found to be very sensitive to the geometric configuration and the imposed boundary conditions. As a result, each problem has to be solved separately. Such solutions, however, are difficult to obtain because it has not been possible to predict a priori the general flow pattern for a given geometric configuration and imposed boundary conditions. The knowledge of the general flow pattern is not only important for analytical studies but also for numerical and experimental investigations because it indicates, at the very least, the type of resolution required to obtain valid results. The first main objective of the research under the subject grant, therefore, was to try to resolve this central problem of flow pattern prediction. A combined theoretical and experimental program was carried out to that end. Emphasis was given to low aspect ratio (shallow) enclosures because of recent practical interest in such geometries and because all the appropriate physics common to all confined natural convection is contained in such situations. Thus, the second objective was to obtain detailed data for shallow enclosures. A comprehensive recent survey of natural convection in enclosures is given by Ostrach [1].

Experimental Program:

Experiments in shallow enclosures heated at the ends with linear horizontal wall temperatures for $0.055 \leq A \leq 0.5$, $27.7 \leq Gr_H \leq 10^6$, and $0.72 \leq Pr \leq 1.38 \times 10^3$ are described by Ostrach et al [2], where A is the height-to-length (aspect) ratio, Gr_H is the Grashof number based on the height, and Pr is the Prandtl number. It was found that:

a. The overall flow patterns are predominantly unicellular

b. The flow pattern is inclined relative to the enclosure geometry for aspect ratios greater than approximately 0.1. For smaller aspect ratios it becomes essentially parallel.

c. The skewness of the streamlines and flow velocities are proportional to the Grashof number and aspect ratio.

d. Secondary cells are observed near the enclosure ends when the aspect ratio is 0.2 and $(Gr_H PrA)^2$ is of the order of 10^{13}. A representative streamline pattern of this type

A corresponding comprehensive study of the heat transfer aspects is presented by Kamotani et al [3]. The influence of the secondary cells on the heat transfer is clearly shown therein, and the inadequacy of analyses that do not treat the flow pattern correctly is demonstrated.

Theoretical Program:

The experimental program has indicated that in shallow enclosures the flow pattern can be parallel or skewed and, under certain conditions, secondary cells or flow subregions can occur. Such ambiguities concerning the nature of the flows have been found for other configurations and are, in fact, inherent to all internal flows. Since there was no way to predict the flow pattern with confidence a theoretical program was initiated to develop a method for obtaining a qualitative picture of the overall flow pattern for a given geometric configuration and imposed boundary conditions. Because of the more extensive experimental data for shallow enclosures, emphasis was given to that configuration. The first phase of this work is described by Lee and Ostrach [4]. The essence of that work and the results will be briefly summarized.

In low aspect ratio rectangular enclosures the flow pattern can, on a geometric basis alone, be essentially divided into two regions, viz., one, the region near the end walls which is referred to as the end region and the other, the core region, is the region outside the end regions and it is bounded by the horizontal boundaries.

In order to be able to predict the core flow pattern and, thus, the entire flow pattern correctly one has to be clear as to what physical mechanisms pertain to each region. Only in this way can an appropriate mathematical model be developed. Since the flow characteristics can be different and coupled in each flow region it is not possible to consider all the important physical mechanisms in the enclosure from the basic equations which apply in either one region. In addition, the equations that describe the phenomena of interest herein are non-linear and bidirectionally coupled. Any simplifications must, therefore, be carefully made and ad hoc assumptions are dangerous. In order to ensure that an assumption made in one equation is consistently transmitted to the other equations a somewhat formal procedure is employed based on the method of multiple scales. Multiple scales are introduced to give mathematical degrees of freedom which enable physical statements to be made properly concerning the important physical mechanisms in the enclosure. Analytically the method of multiple scales can be used to obtain single uniformly valid expansions, in contrast to the method of matched asymptotic expansions which yields two expansions that must be matched. The method of multiple scales formally yields the equations valid in each region as well as in the interaction region.

With the available degrees of freedom obtained from the multiple scaling proper physical statements (force or energy balances) can be made in the equations that have been properly normalized. The order of magnitude of each term in the equaiton can then be estimated from the dimensionless parameters that appear as coefficients of the various terms. It is easy to extract the equations that describe the core flow characteristics from the general equations.

The core flow patterns are first studied in a global sense under the implicit assumption that there exist no flow subregions, such as secondary cells. On that basis, the geometric length scales are the appropriate ones for the core flow structure. With the use of the results of the global considerations detailed analysis is then made to determine the possibility of flow subregions. In the detailed analysis arbitrary length scales which are determined from the physical statements replace the geometric length scales. The proper scaling of all the variables are obtained in this way. The results to be presented pertain essentially to enclosures with adiabatic horizontal surfaces and with the (vertical) ends at different temperatures. For some situations other horizontal thermal conditions were examined.

The results are summarized in Table 1. The basic force and energy balances in each region are indicated thereon as are also the proper scaling for the characteristic stream function, ψ_r, and the horizontal length scale of end region, δ_x, and the physical conditions for which the various core configurations will be obtained. Note that three specific situations are analyzed depending on where the buoyancy (driving) force is operative. When $Ra_H A^2 \leq 1$ and $PrRa_H A^2 << 1$ the core temperature distribution is linear and the flow is driven by the buoyancy in the core. Depending on the magnitude of the Grashof number the core flow will be parallel when there is no flow boundary layer ($GrA^2 \leq 1$) and nonparallel when there is a flow boundary layer ($GrA^2 > 1$). No flow subregions are expected under these conditions.

When there are thermal boundary layers near the ends of the enclosure ($Ra_H A^2 >> 1$) the flow will be driven by the buoyancy acting there. Then depending on the magnitude of Pr the core flow will be stagnant in the mid-core, distinct horizontal thermal boundary layers will exist, and the core temperature distribution will be stratified. Secondary cells can be expected for large Pr.

In the intermediate flow regime the core temperature distribution varies with both space variables so that the buoyancy force acts throughout the enclosure and there is an interaction between the core and end flows. In this case both parallel and non-parallel core flows can occur under the conditions specified and multicell patterns seem possible.

Comparison of the predictions of the core flow patterns show good agreement with existing experimental data for $Pr \geq 1$. For $Pr < 1$ there is insufficient data for a comparable configuration. The global prediction of the core flow patterns is generally satisfactory. Further work however, will be required to define the flow subregions better. The method of analysis has clarified much of the physics of such problems and can be generalized to other configurations. It thus seems like a good first step in resolving the central problem that has confronted workers on this subject since its inception.

Combined Thermal and Hydrodynamic Instability in the Boundary Layer along a Curved Plate

This work is described in detail by Lin et at [5] so that only a summary of the work is presented herein.

The important dimensionless parameters of the problem are G (Görtler number), Gr (Grashof number) and Pr (Prandtl number). The ratio Gr/G^2 is important in the present study because it represents the relative importance of buoyancy to centrifugal forces on the behavior of Görtler vortices. The ranges of the parameters in the present experiments are $Pr = .7$ (air), $G \leq 8.1$ and $0 \leq Gr/G^2 \leq 8.5$. The velocity and temperature distributions in the boundary layers are measured in detail by a hot-wire and a thermocouple probe. Based on the data the effects of destabilizing heating on Görtler vortices are delineated. The data taken under isothermal conditions ($Gr = 0$) and some data with heating were given in the previous reports. As reported, Görtler vortices cause spanwise variations of the velocity and temperature distributions.

An important quantity to characterize the strength of Görtler vortices is the amplitude of the spanwise velocity or temperature variations. Under isothermal conditions it is found that the amplitude of the spanwise velocity variation is closely approximated by the relation

$$\frac{A}{Ao} = \exp\left[a\,(G - Gc)\right]$$

where Gc is the critical Görtler number, Ao the amplitude at G = Gc, and a = .41. The above correlation curve is compared with the experimental data in Fig. 2. With heating, the amplitude of the spanwise temperature variation is found to be expressed as

$$\frac{A}{Ao} = \exp\left[a\,(C - Gc)\right]$$

where C is the combined parameter $C = (G^2 + f\ \ Gr)^{1/2}$, and f represents the relative importance of buoyancy to centrifugal forces. f is found to depend on the free stream velocity. The correlated curves are compared with the experimental data in Fig. 3. Comparison of the above two expressions shows that one important effect of heating is to increase the strength of the vortices.

Another important effect of heating is that it enhances the non-linear development process of the vortices. Fig. 4 shows the effect of heating on the spanwise temperature distributions. As seen in the figure, with increasing heating the temperature distribution in the warm region becomes spiky, which means that the upwash region of the vortices tends to be concentrated in a narrow region, but the temperature distribution in the cold region suggests that the downwash region of the vortice tends to be more spread out. This is the non-linear effect investigated in the past under isothermal conditions.

The present study shows that the non-linear effect is enhanced by heating. Also due to the enhancement the vortices start to meander in the spanwise direction, which causes temperature fluctuation with time. The temperature fluctuating levels at three spanwise sections are shown in Fig. 5. Sections V and P correspond to the upwash region and the downwash region of the vortices, respectively. Section C is in the middle of the two sections. Since the temperature fluctuation is mainly caused by an unsteady meandering motion of the vortices, the fluctuating level is smallest in the downwash region because of relatively uniform temperature in the region as described above, and largest in the upwash region due to relatively non-uniform spanwise temperature variation in the region.

The conclusions drawn from the present experimental study are as follows.

1. Within the ranges of the parameter Gr/G^2 studied herein ($Gr/G^2 \leq 8.5$) the wavelength of the vortice remains unchanged. The strength of the vortices is enhanced by heating.

2. The amplitude of the vortices increases almost exponentially with the combined parameter $(G^2 + f\ Gr)^{1/2}$ where f is found to be $.3 < f < .4$, until the non-linear effects become important.

3. Heating enhances the non-linear effect. The warm upwash region of the vortices tends to be concentrated in a narrow region and the cold downwash region tends to spread out as Gr increases while G is fixed, and as Gr is increased further, the vortex rolls start to meander, which causes temperature fluctuations with time at a fixed point.

4. The non-linear effects - the vortex shape distortion and the meandering of the vortex rolls - become noticeable at a smaller value of the parameter $G^2 + f$ Gr as the value of the parameter Gr/G^2 is increased.

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3. Kamotani, Y., Wang, L.W., and Ostrach, S.: Experiments on Natural Convection Heat Transfer in Low Aspect Ratio Enclosures, AIAA Jour., vol. 21, no. 2, 290-294, 1983.

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5. Lin, J.K., Kamotani, Y., and Ostrach, S.: Effect of Heating on Gortler Instability, Case Western Reserve Univ., Dept. of Mech. & Aerosp. Eng., FTAS/TR-82-162, Aug. 1982 (In preparation for journal publication)

In addition to the above the following journal articles have also been published on aspects of the research done under the subject grant.

1. Ostrach, S. and Hantman, R.: Natural Convection Inside a Horizontal Cylinder, Chemical Eng. Communications, vol. 9, 213-243, 1981.

2. Fu, B.-I. and Ostrach, S.: The Effects of Stabilizing Thermal Gradients on Natural Convection Flows in a Square Enclosure, in Natural Convection, ASME HTD vol. 16, 10981.

TABLE 1. SUMMARY OF THE ANALYSIS

	BASIC BALANCES	SCALES	PHYSICAL CONDITIONS			CORE CONFIGURATIONS
CORE DRIVEN FLOW REGIME	Buoyancy ~ Viscous in the Core Horizontal Viscous ~ Vertical Viscous in the End	$v_R \sim \frac{\beta g \Delta T H^4}{\nu L}$ $\delta_x \sim H$	$Gr_H A^2 \lesssim 1$ $A^2 << 1$	$Ra_H A^2 << 1$		parallel flow pattern linear temperature distribution
				$Ra_H A^2 \sim 1$		parallel flow pattern linear & stratified temperature distribution
	Buoyancy ~ Inertia in the Core Inertia in the End ~ Inertia in the Core	$v_R \sim (\beta g \Delta T H^3)^{1/2}$ $\delta_x \sim L$	$Gr_H A^2 >> 1$ $A^2 << 1$	$PrRa_H A^2 << 1$		non-parallel flow pattern linear temperature distribution
BOUNDARY LAYER FLOW REGIME	Convection ~ Conduction in the End Buoyancy ~ Viscous in the End	$v_R \sim \alpha Ra_H^{1/4}$ $\delta_x \sim \frac{H}{Ra_H^{1/4}}$	$Ra_H A^2 >> 1$ $A^2 << 1$	$ARa_H^{1/4} > 1$	$Pr \sim 1$	distinct horizontal thermal layers exist stratified temperature distribution with stagnant fluid motion in the mid-core flow subregimes expected when $ARa_H^{1/4} < Pr^{1/4}$
					$Pr >> 1$	distinct horizontal thermal layers exist parallel flow pattern stratified temperature distribution in the mid-core secondary cells expected near the end when $APr \sim Ra_H^{1/4}$
	Conv. ~ Cond. in the End Buoy. ~ Inertia in the End	$v_R \sim \alpha(PrRa_H)^{1/4}$ $\delta_x \sim \frac{H}{(PrRa_H)^{1/4}}$		$A(PrRa_H)^{1/4} > 1$	$Pr < 1$*	distinct horizontal thermal layers exist stratified temperature distribution with stagnant fluid motion in the mid-core
INTERMEDIATE FLOW REGIME	Conv. ~ Cond. in both the End and Core Buoy. ~ Viscous in the End (or in the Core)	$v_R \sim \alpha Ra_H^{1/4}$ $\delta_x \sim \frac{H}{Ra_H^{1/4}}$	$Ra_H A^2 >> 1$ $A^2 << 1$	$ARa_H^{1/4} \lesssim 1$	$Pr \sim 1$	non-parallel flow pattern patterns of multi-cells seem to be possible temperature varies in both ζ and y direction
					$Pr >> 1$	parallel flow pattern temperature varies in both ζ and y direction
	Conv. ~ Cond. in both the End and Core Buoy. ~ Inertia in the End (or in the Core)	$v_R \sim \alpha(PrRa_H)^{1/4}$ $\delta_x \sim \frac{H}{(PrRa_H)^{1/4}}$		$A(PrRa_H)^{1/4} \lesssim 1$	$Pr < 1$*	non-parallel flow pattern patterns of multi-cells seem to be possible temperature varies in both ζ and y direction

* This always includes the case of Pr << 1

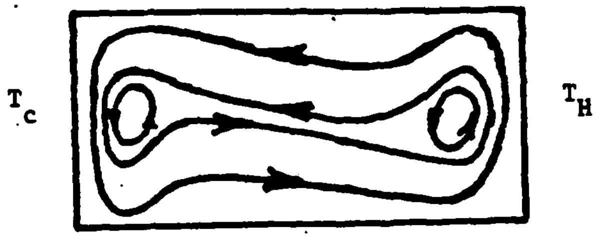

Fig. 1 The overall flow pattern for $A = 0.2$ and $(Gr_H PrA)^2 = 0\ (10^{13})$

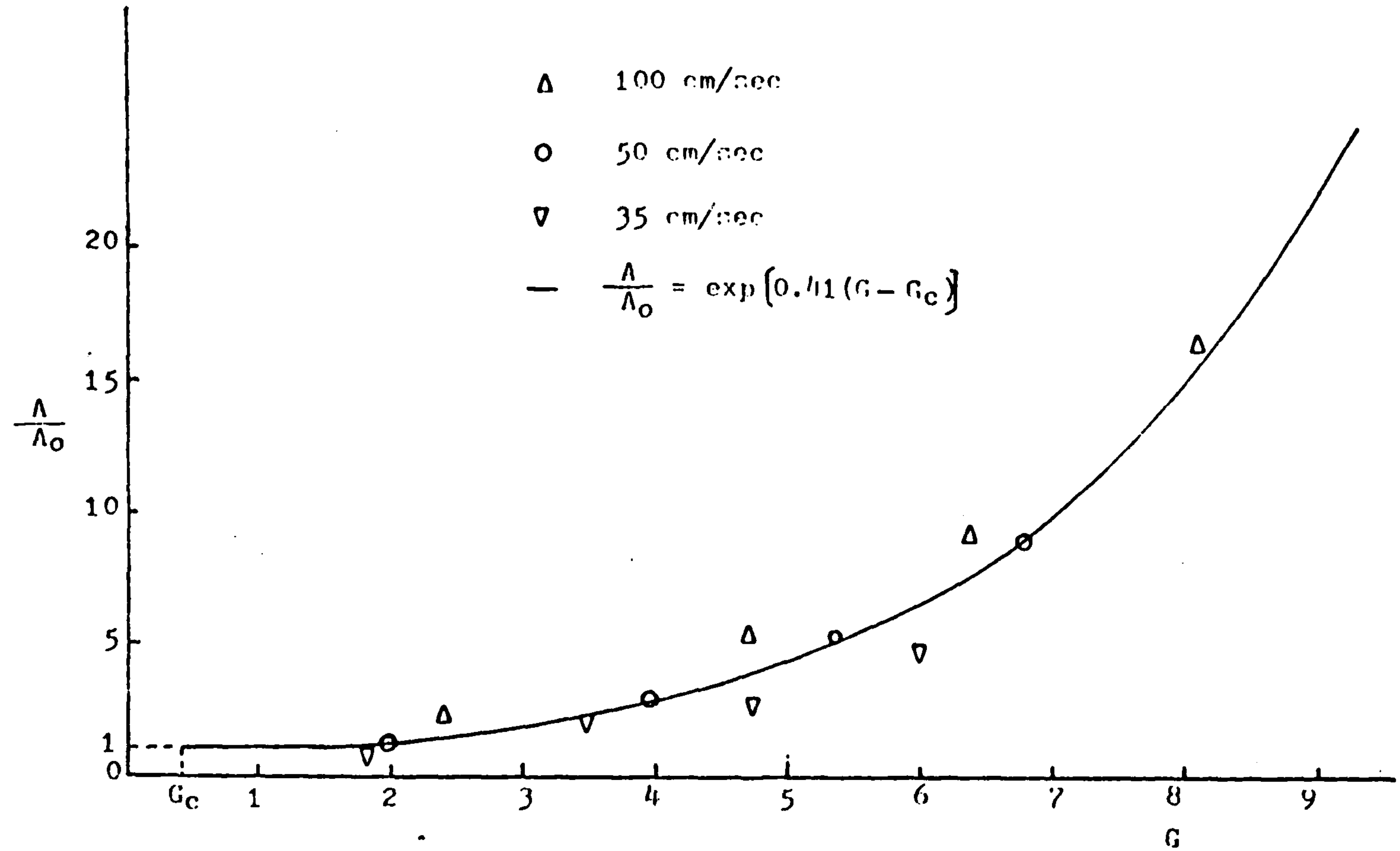

Figure 2 Experimental data and correlation curve for variation of maximum relative amplitude with Görtler number

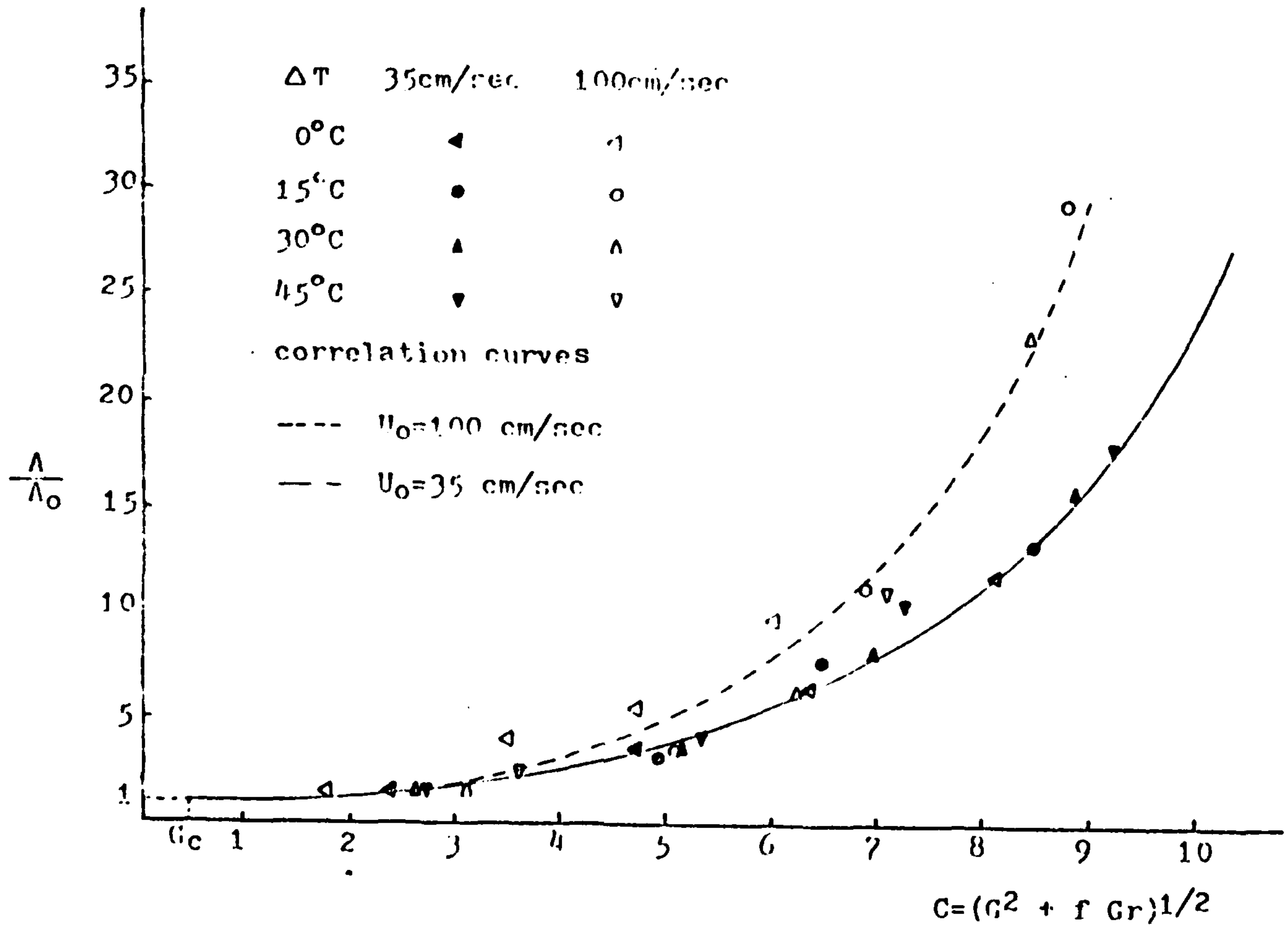

Figure 3 Experimental data and correlation curves for variation of maximum relative amplitude with combined parameter C

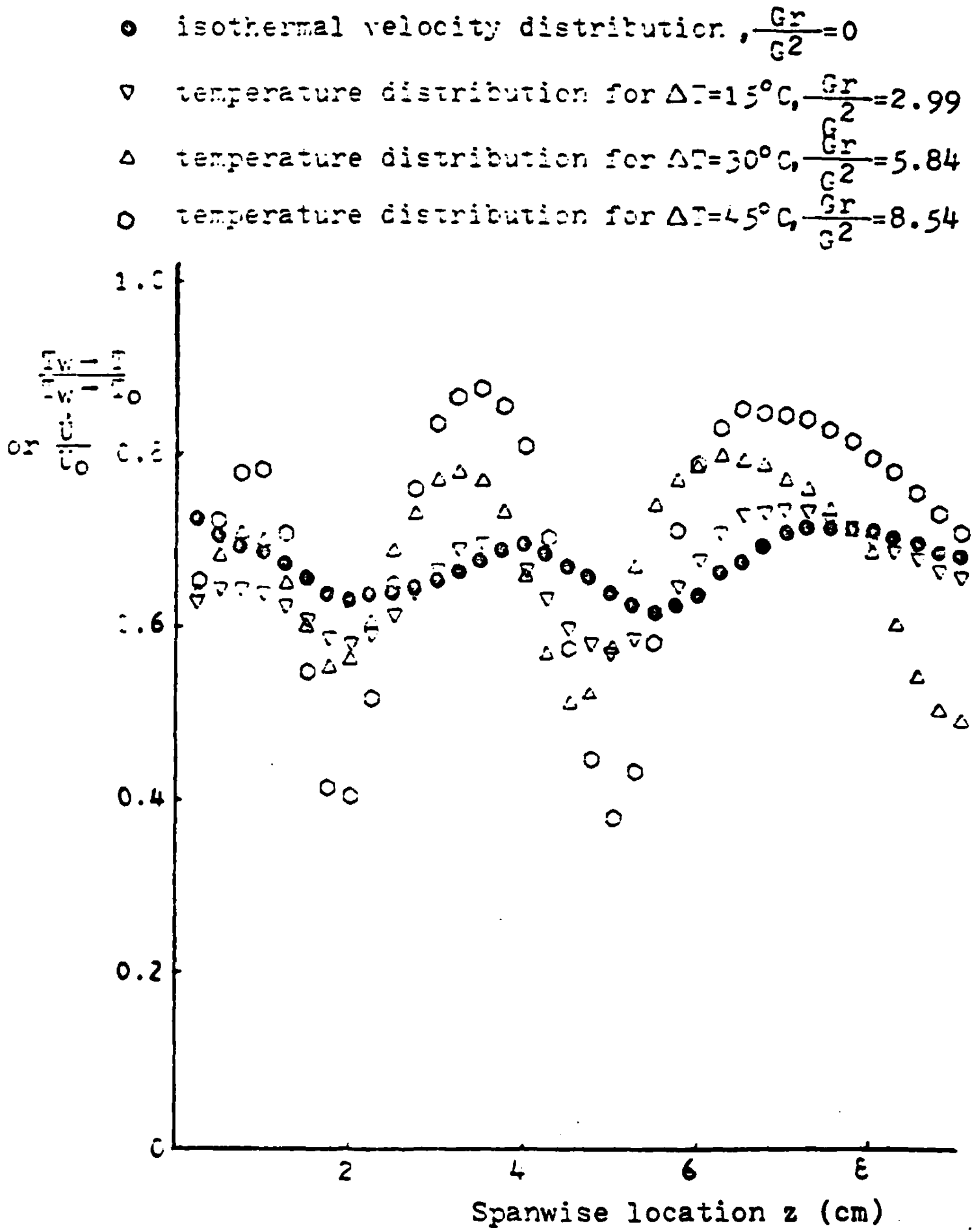

Figure 4 Spanwise distributions of disturbance at U_o=35 cm/sec, x=24 cm and y=6 mm

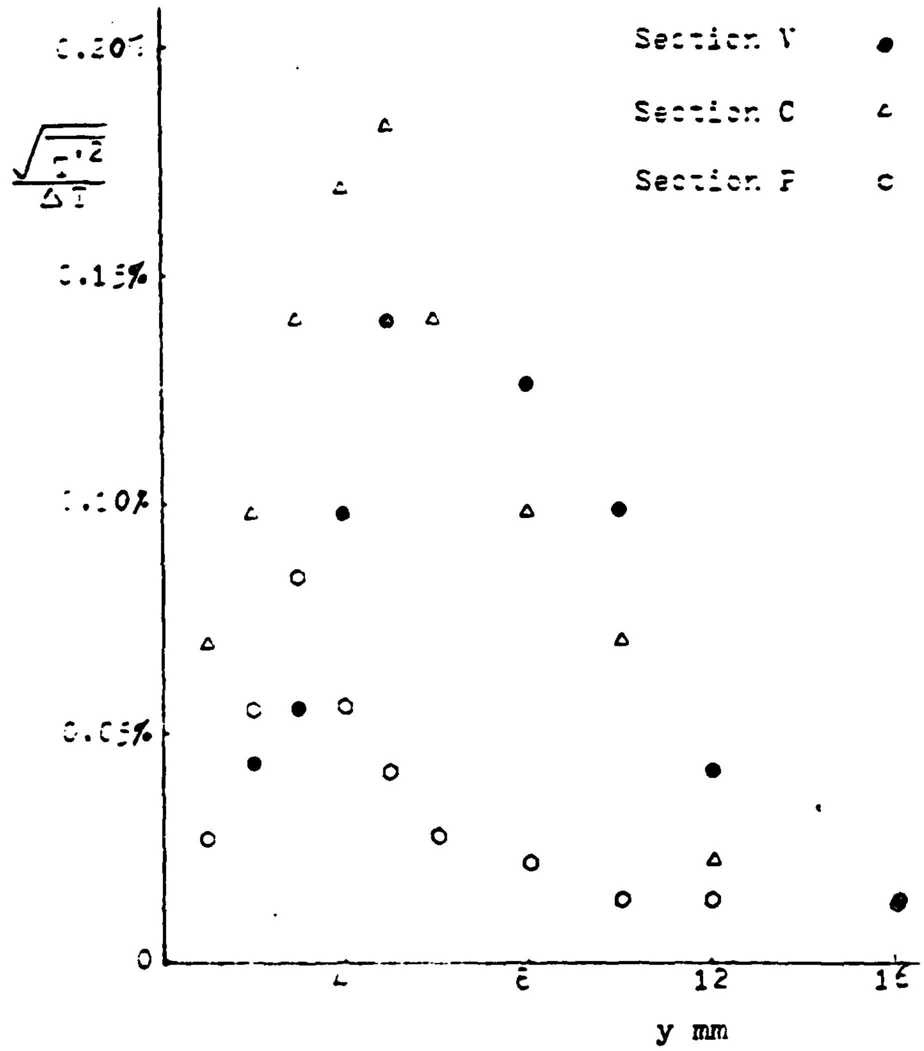

Figure 5 Temperature fluctuation levels across boundary layer at x=24 cm, U_0=50 cm/sec, ΔT=45°C for various spanwise sections

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The research performed under the subject grant dealt with two problems in which body forces lead to complex flows which are of scientific and technological importance. The first of these is concerned with the central unresolved problem of flows in completely confined enclosures, viz., that it is not possible to predict the flow pattern a priori for a specified geometric configuration and imposed boundary conditions. The second problem is an external one in which there is an interaction of hydrodynamic (Taylor-Gortler)

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) and thermal (Rayleigh-Bernard) instabilities.

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